Optimization of power plant investments under uncertain renewable energy deployment paths

A multistage stochastic programming approach

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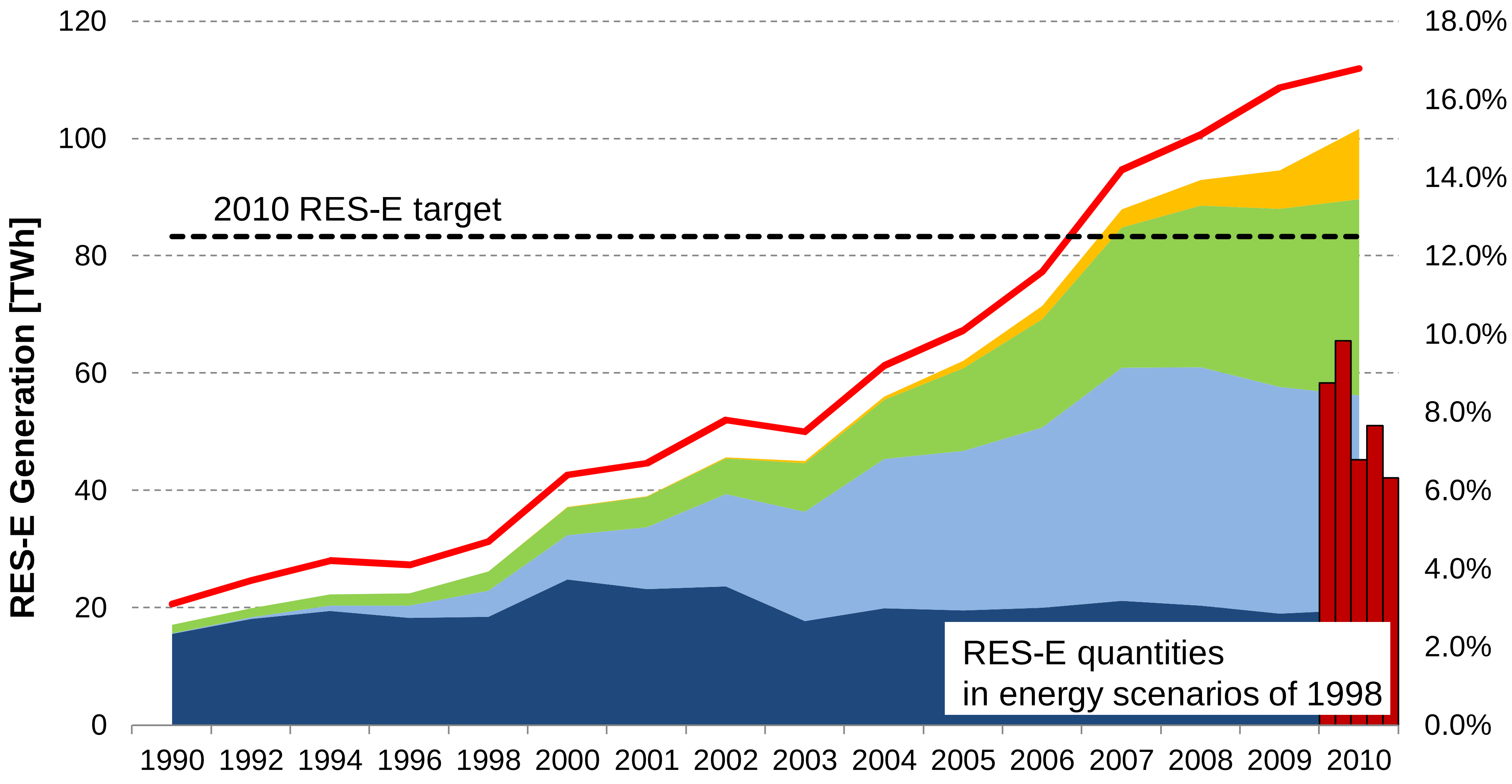
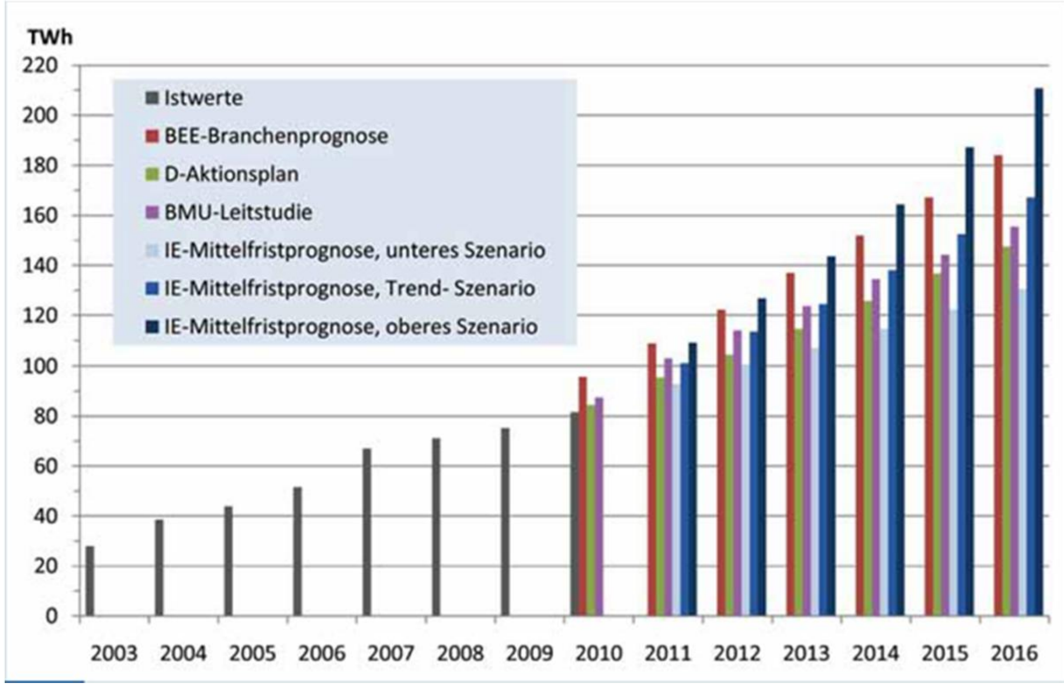
Paris, 13.11.2013

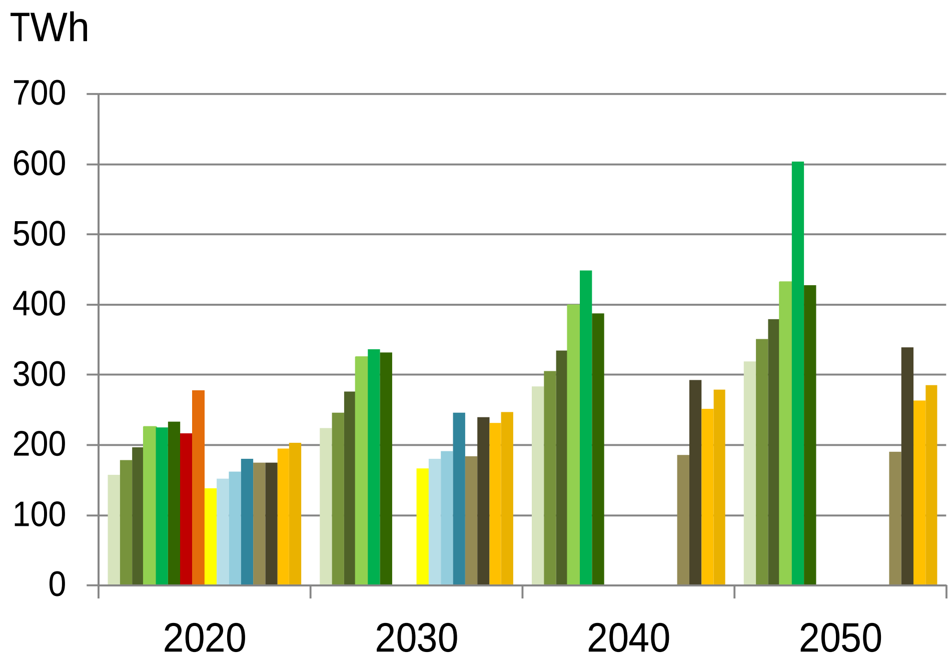
RES-E deployment – Forecasts, Targets and Reality



Data source: BMU and Agentur für Erneuerbare Energien

Future developments





Source: Reichmuth (2012)

Data source: BMU, BMWi, EURPROG, Prognos/WWF, BEE

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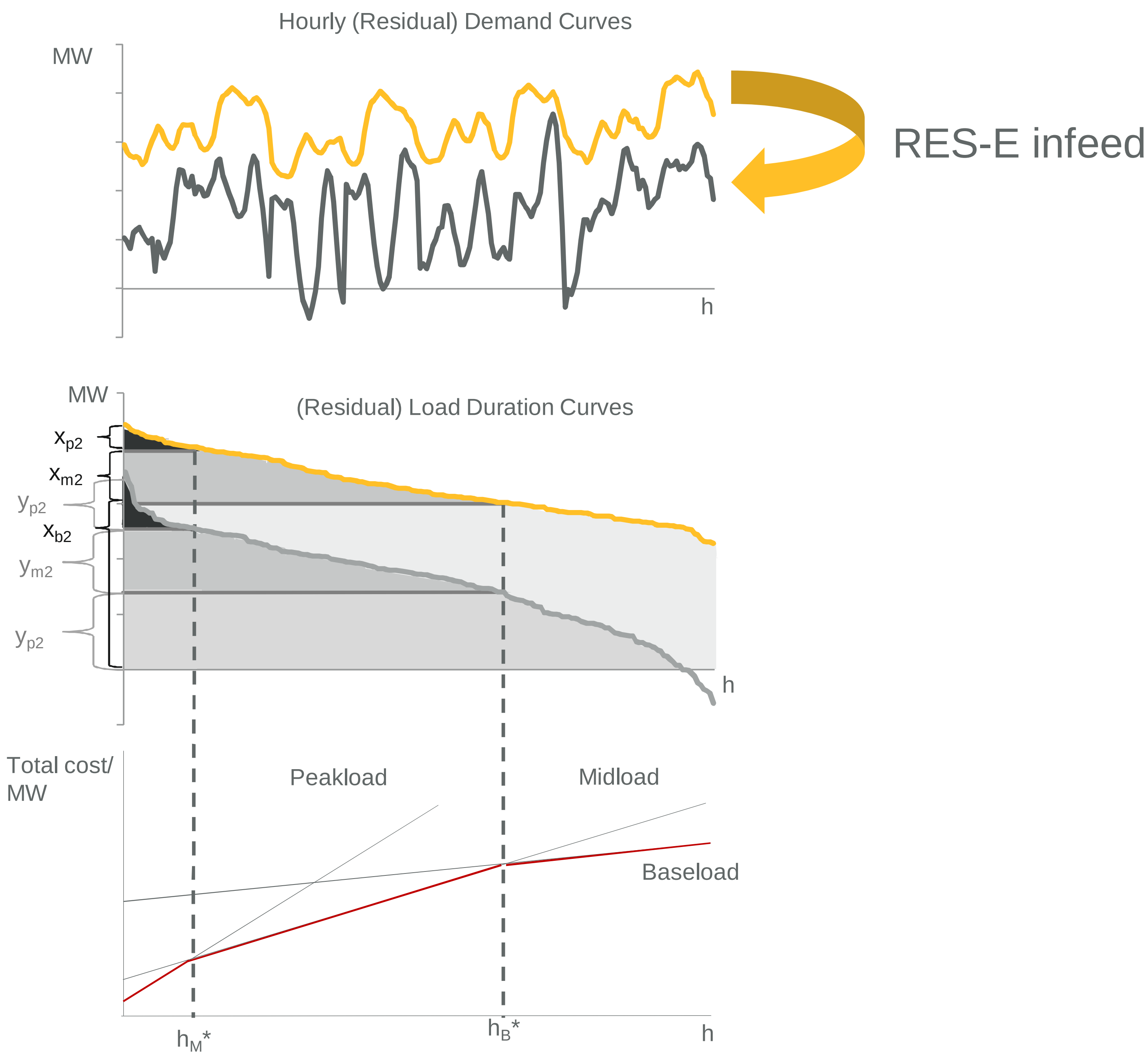
- Grid extensions?
- Public acceptance?
- Cost developments?
- Technological progress?

Influence of different residual load developments



Contents

Methodology: Stochastic Programming

- **General idea: „… find an optimal solution in problems involving uncertain data“ (Birge/Louveau)**
- **Requires assumptions on the distribution of uncertain parameters**
- **Two-Stage and Multistage Stochastic Programming:**
  - Two-Stage: Choose first-stage variables without knowing future revelation of random parameters (e.g., investment variables); choose second-stage variables under certainty (e.g., dispatch variables)
  - Multi-Stage: „sequences of decisions that react to outcomes that evolve over time“ (Birge/Louveau); First-stage variables are decided at different points in time; takes into account the possible value of waiting

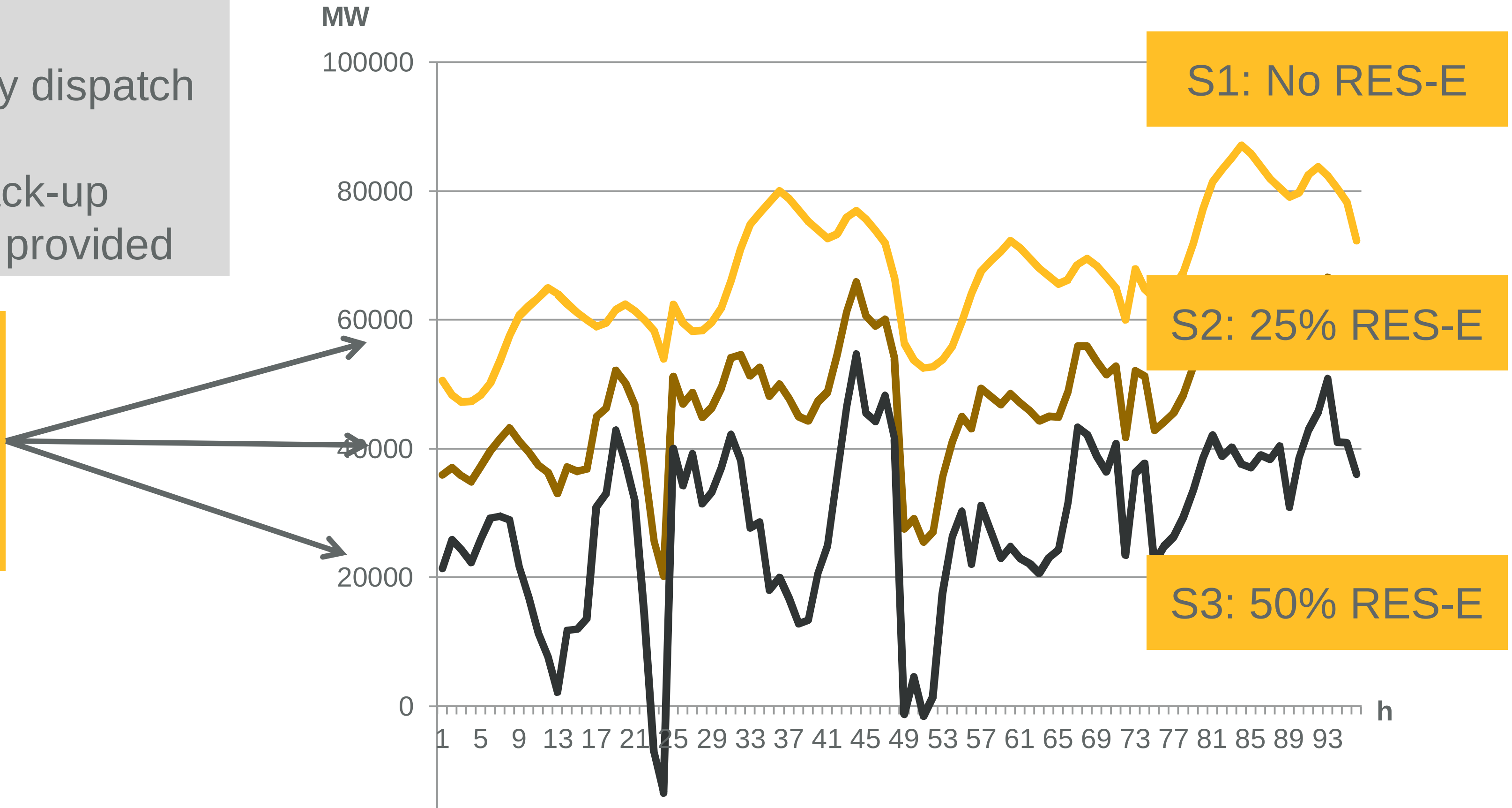
Here:

Illustrative example: Two-Stage Greenfield	Application to Central Europe: Multi-Stage

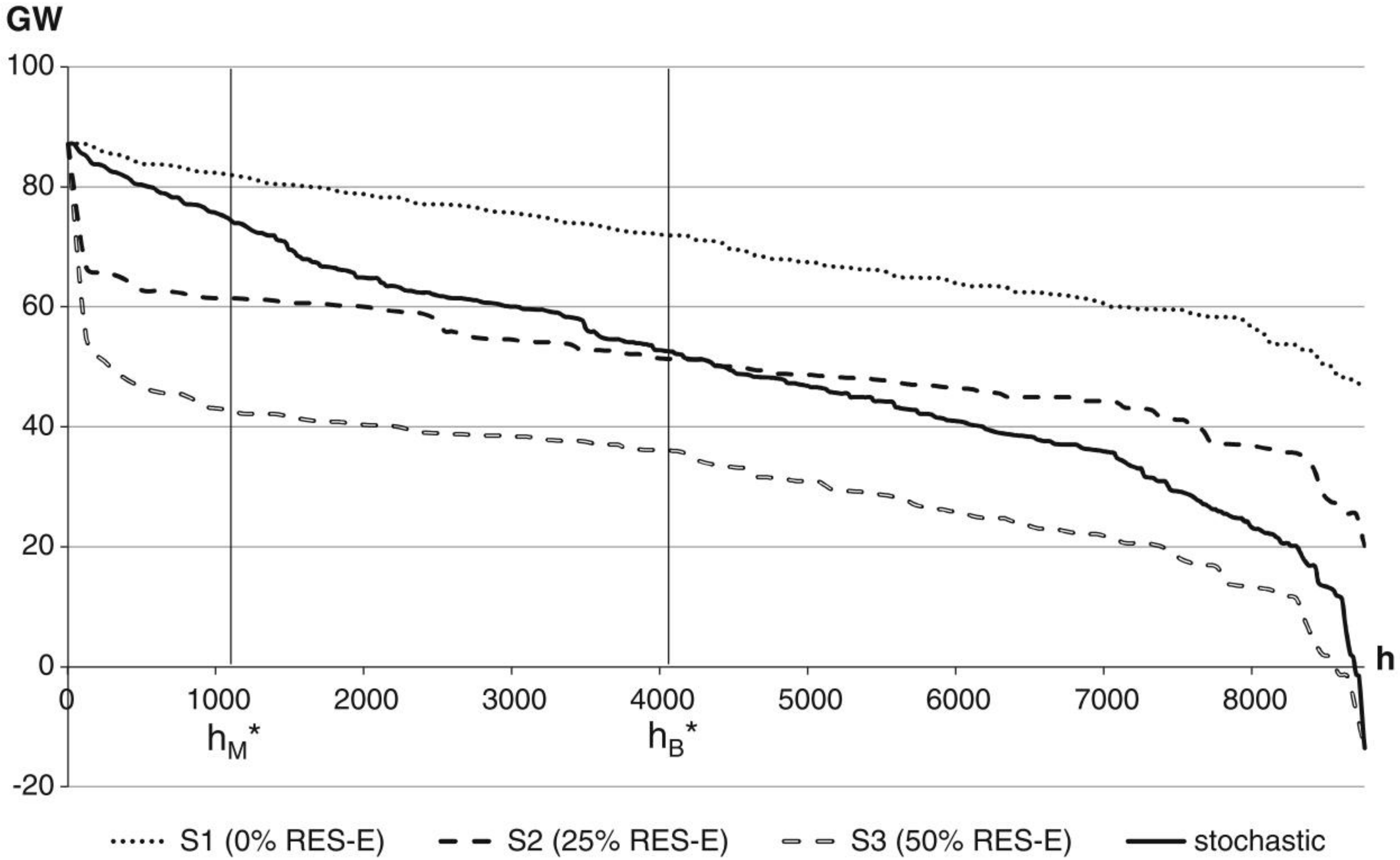
Illustrative example – Scenario Setting

- Greenfield approach
- annuitized costs
- one region
- 4 typical days, hourly dispatch
- Linear optimization
- Securly available back-up capacitiy needs to be provided

Investment decision (Coal, CCGT, OCGT, storage)



Residual load duration curves – deterministic and stochastic



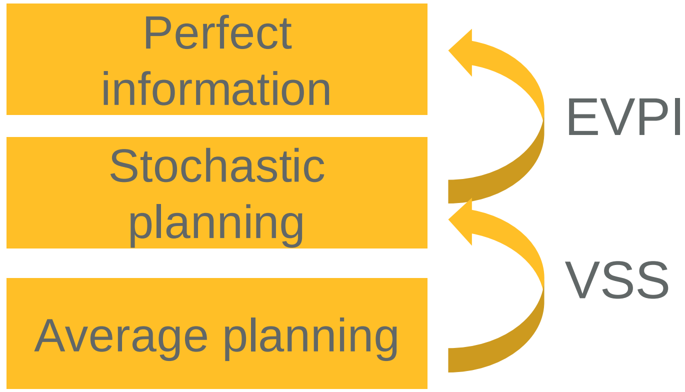
Illustrative example – investments and utilization times with deterministic and stochastic planning

	Deterministic						Stochastic			
	S1 (0 %)		S2 (25 %)		S3 (50 %)		S1-S3	S1	S2	S3
	GW	h	GW	h	GW	h	GW	h		
Coal	83	6,969	61	6,811	41	6469	50	7,111	6,985	5,393
CCGT	11	3,321	9	3,057	4	4,096	36	6,455	2,792	230
OCGT	2	124	26	74	46	51	13	2,248	0	0
Storage	8	1,191	7	1,163	15	1,189	5	1,280	647	581

Illustrative example - EVPI and VSS [Mio €]

- **Expected Value of Perfect Information (EVPI): „value of knowing the future with certainty“**

- **Value of the Stochastic Solution (VSS): „possible gain from solving the stochastic model“ (Birge/Louveaux 1997)**



	planning under perfect information	stochastic planning	average planning
s1: no RES-E	41,166	42,040	43,966
s2: av. RES-E	31,253	31,736	31,285
s3: 50% RES-E	21,960	23,269	23,105
average	31,460	32,348	32,785

EVPI	889 Mio € (2.82 % of average det. costs)
VSS	437 Mio € (1.39 % of average det. Costs)

Illustrative example - Sensitivities

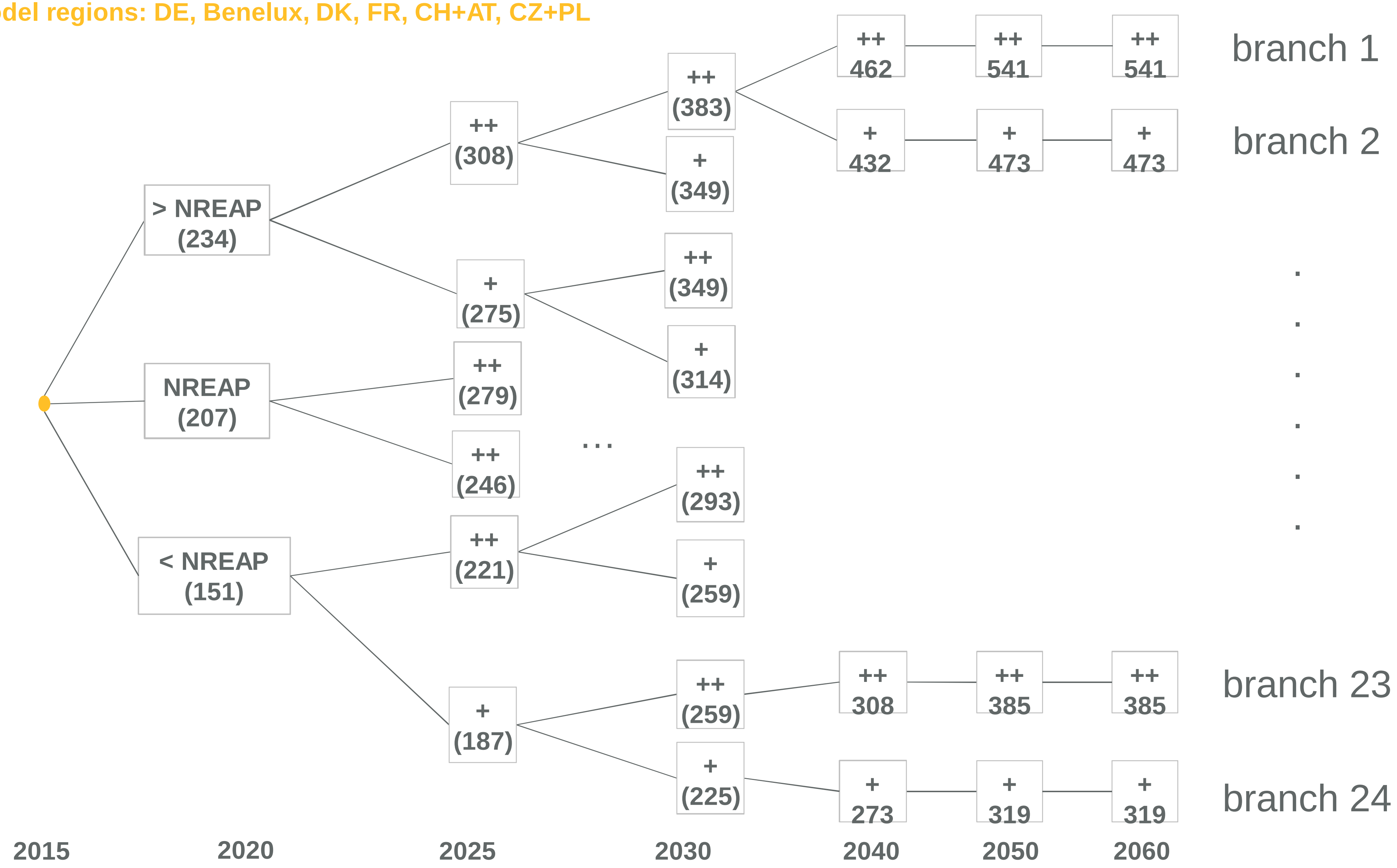
- The setting of the illustrative scenario is rather extreme: Large difference between RES-E penetration in different scenarios, only 3 scenarios are taken into account to represent the uncertainty
- We find that both different distributions of the uncertain events and a different choice of RES-E infeed patterns affect magnitude, however not direction of results
- In addition: Greenfield approach and two-stage modelling: no possibility to post-pone investments

➡ Which effects could possibly arise in the Central European Power System?

Contents

Multisstage Scenario Setting

Model regions: DE, Benelux, DK, FR, CH+AT, CZ+PL



Basic model equations

$$
\begin{aligned}
minZ = \sum_{n} \Bigg[p(n) \cdot dsc(y) \cdot \sum_{t,r} \Bigg[\Bigg[\sum_{n2} annuity(t) \cdot CADD(t, n2, r) \Bigg] \qquad (1) \\
+ C(t, n, r) \cdot fomc(t) \\
+ \Bigg[\sum_{d,h} G(d, h, n, t, r) \Bigg] \cdot \Bigg[\frac{f(y, t) + co(y) \cdot \omega(t)}{\eta(t)} \Bigg] \\
+ \Bigg[\sum_{d,h} CUP(d, h, n, t, r) \Bigg] \cdot \Bigg[\frac{f(y, t) + co(y) \cdot \omega(t)}{\eta(t)} + attc(t) \Bigg] \\
+ \Bigg[\sum_{d,h} (CRTO(d, h, n, t, r) - G(d, h, n, t, r)) \Bigg] \\
\times \Bigg[\frac{f(y, t) + co(y) \cdot \omega(t)}{\eta_{partload}(t)} - \frac{f(y, t) + co(y) \cdot \omega(t)}{\eta(t)} \Bigg] \cdot \frac{\beta}{1 - \beta} \\
- \sum_{d,h} heatpr(y) \cdot heatratio(t) \cdot G(d, h, n, t, r) \Bigg] \Bigg]
\end{aligned}
$$

s.t.

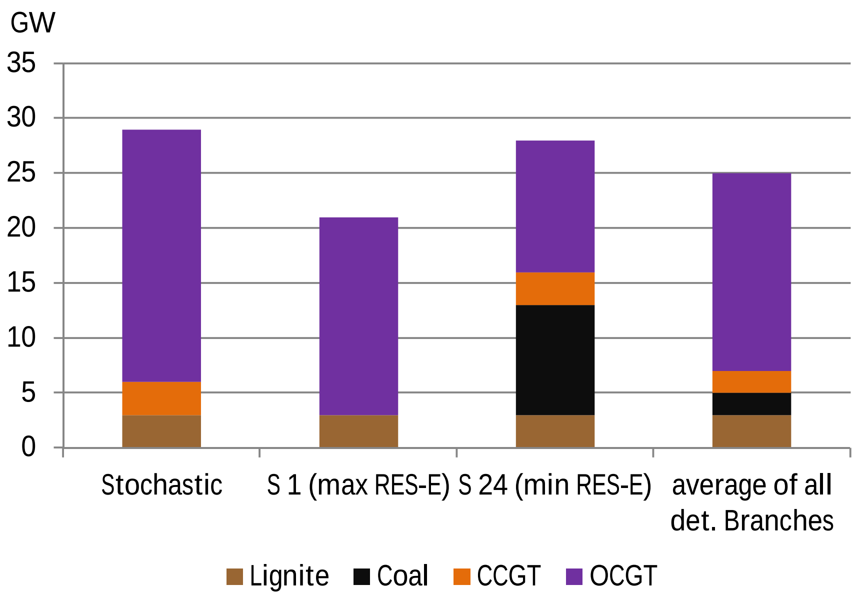
$$
\sum_{t} G(d, h, n, t, r) + \sum_{r1} NI(d, h, n, r, r1) - \sum_{s} S(d, h, n, s, r) = \rho(d, h, n, r) \qquad (2)
$$

$$
\tau \cdot C(t, n, r) + \gamma \cdot cres(res, n, r) \geq \theta(n, r) \qquad (3)
$$

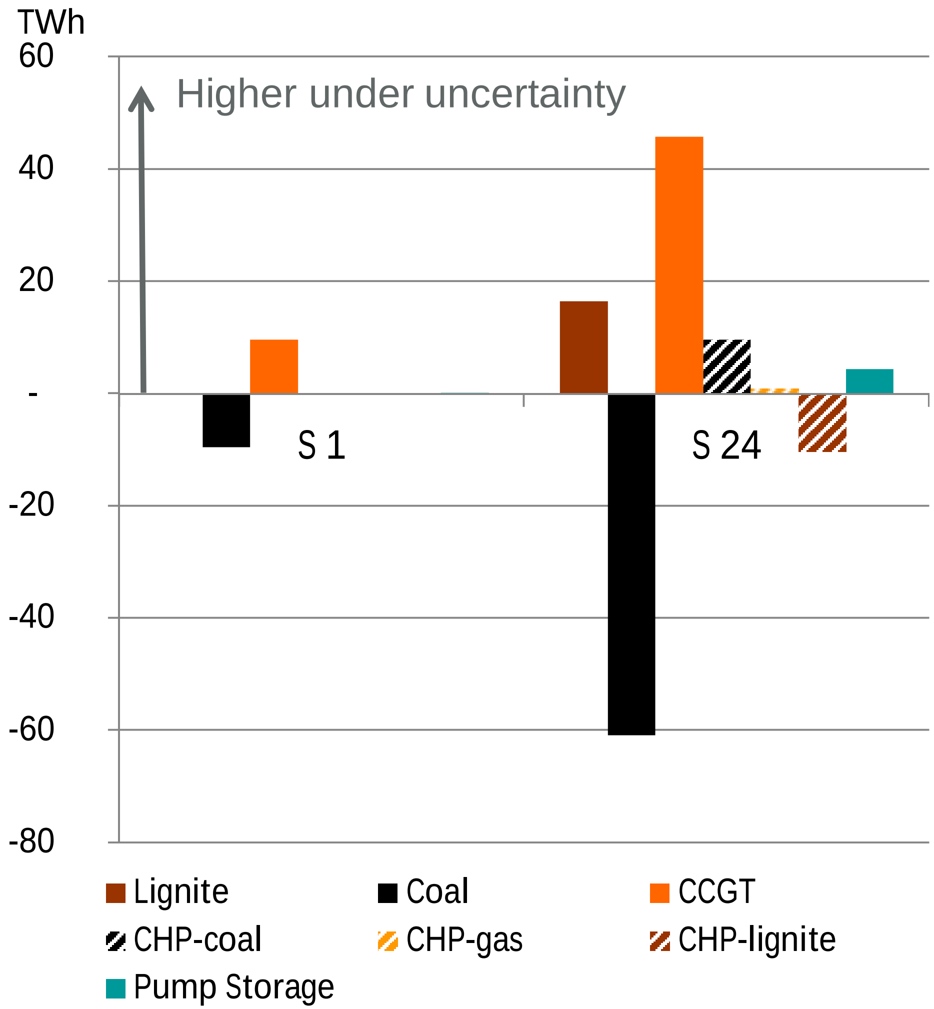
$$
\begin{aligned}
C(t, n) = C(t, n1) + CADD(t, n1) + ad(t, y) - CSUB(t, n) \qquad (4) \\
- \sum_{n2} \Big[(CADD(t, n2) + ad(t, n2)) \cdot \xi(t, n, n2) \Big]
\end{aligned}
$$

Effect of uncertainty on investment decisions (2015) and generation (2020); in all model-regions

Investments 2015

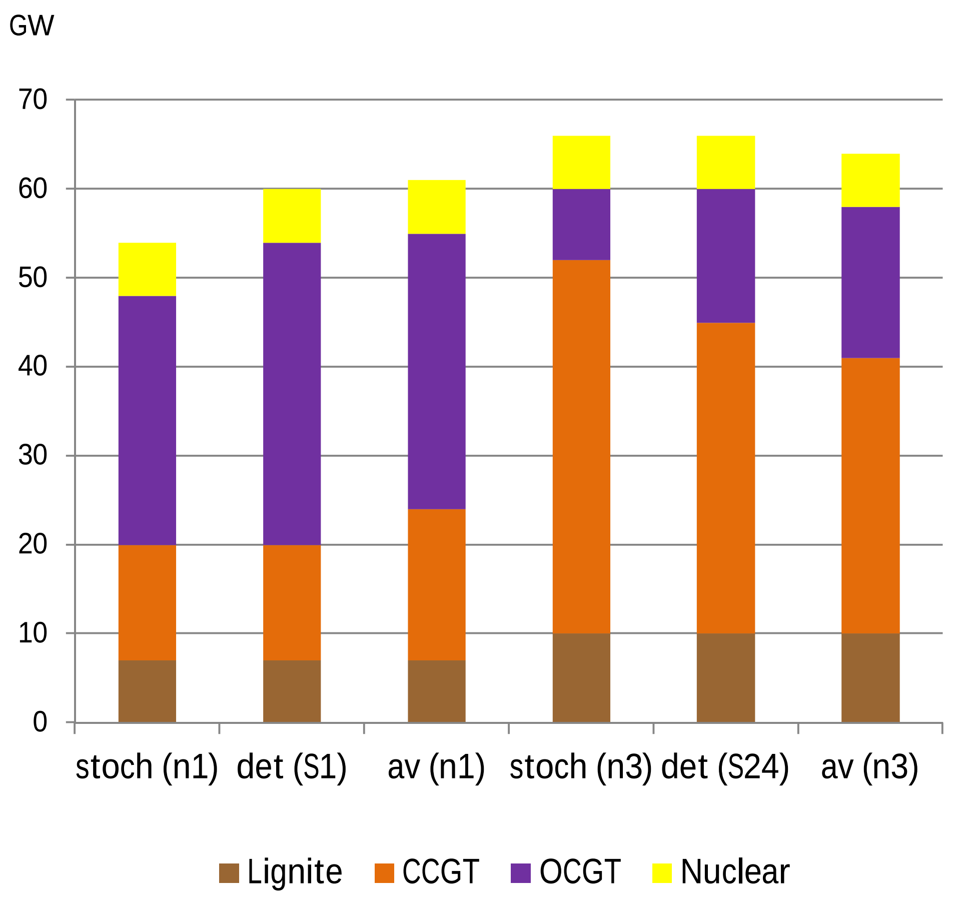


Generation differences 2020

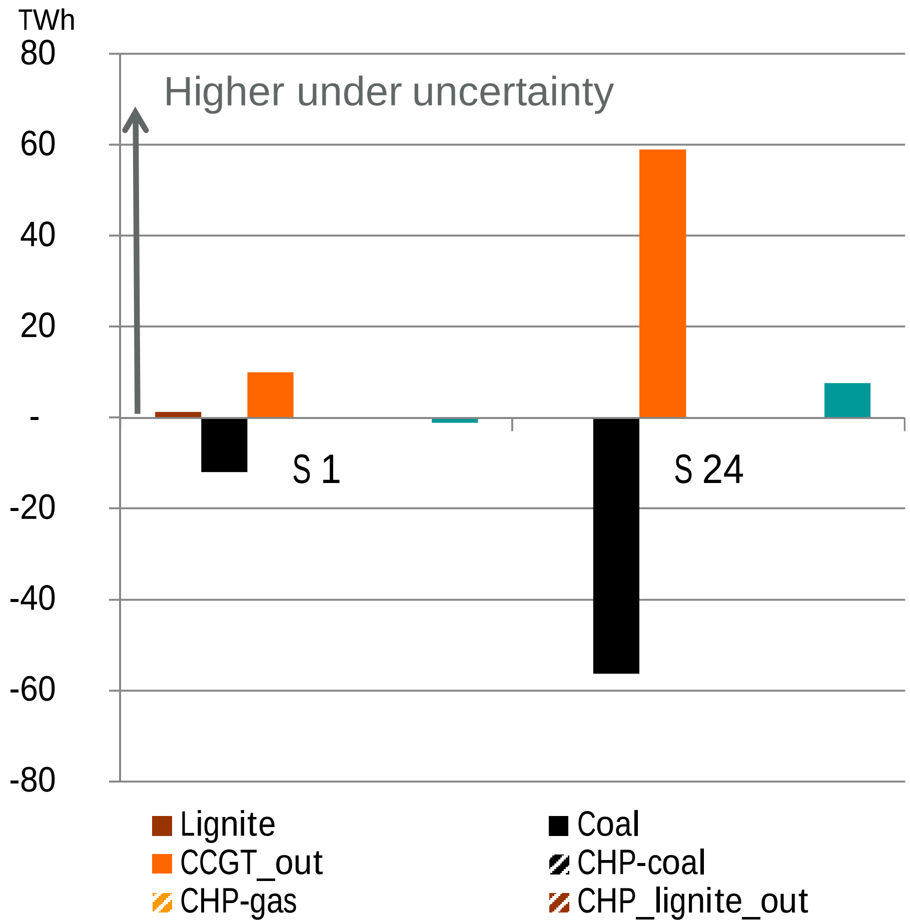


Effect of uncertainty on investment decisions (2020) and generation (2025) ; in all model-regions

Investments 2020

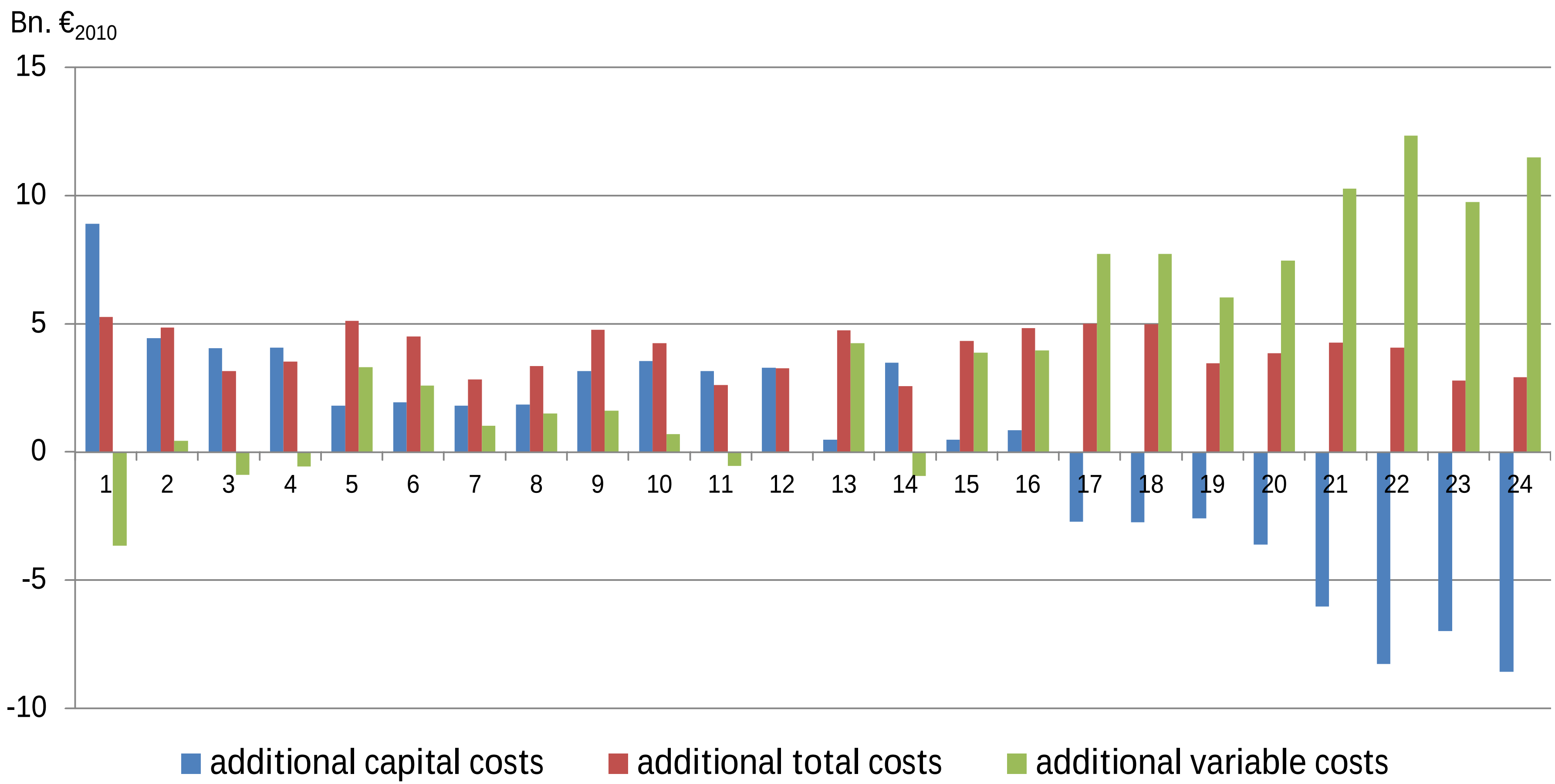


Generation differences 2025



Effect of uncertainty on system costs (EVPI)

(accumulated costs until 2060; discounted with 5%)



- Average additional costs due to uncertainty = 4 bn €
- EVPI expressed as % of average det. costs = 0.3%

Conclusion

- Uncertainty about future RES-E deployment paths leads to uncertainty about the level and the slope of the residual load

➡ Optimal investment planning for dispatchable power plants and storage units under uncertainty is different than given perfect foresight

➡ In particular, the value of plants with a medium capital/operating ratio increases under uncertainty

➡ Impact on system costs is rather small if we assume that a long-term increase of the RES-E share is reliable and that only the pace and the magnitude of the increase is uncertain

Thank you for your audience.

Questions, comments?

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Further questions:

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Back-up

Literature: Investment decisions under uncertainty

- **demand uncertainty (two-stage)**
  - Murphy et al. (1982) IEE Transactions
  - Mondiano (1987) Operations Research
- **demand uncertainty (multi-stage)**
  - Gardner (1996) Energy
  - Gardner and Rogers (1999) Management Science
- **Fuel cost uncertainty**
  - Hobbs and Maheshwari (1990) Energy
- **CO_2 price uncertainty**
  - Reinelt and Keith (2007) Energy Journal
  - Roques et al. (2006) Energy Journal
  - Patino-Echeverri et al. (2009) Environm. Science and Techology

Assumptions I – demand and fuel costs

Table 2: Net electricity demand in TWh_{el} and (potential heat generation in CHP Plants in TWh_{th})

	2020		2030		2040		2050	
Benelux	226.2	(128)	241.7	(128)	241.7	(128)	241.7	(128)
CH + AT	140	(-)	149.5	(-)	149.5	(-)	149.5	(-)
CZ + PL	233.9	(146)	260.4	(146)	260.4	(146)	260.4	(146)
Denmark	43.1	(54)	46	(54)	46	(54)	46	(54)
Germany	611	(191)	628	(191)	628	(191)	628	(191)
France	523.6	(-)	558.3	(-)	558.3	(-)	558.3	(-)

Table 5: Fuel costs in €$_{2010}$/MWh_{th} and CO_2 emission costs in €$_{2010}$/t CO_2

	2008	2020	2030	2040	2050
Oil	44.6	99.0	110.0	114.0	116.0
Coal	17.28	13.4	13.8	14.3	14.7
Natural Gas	25.2	28.1	30.1	32.1	34.1
Lignite	1.4	1.4	1.4	1.4	1.4
Uranium	3.6	3.3	3.3	3.3	3.3
CO_2	22	25	35	40	45

Assumptions II – Power Plants

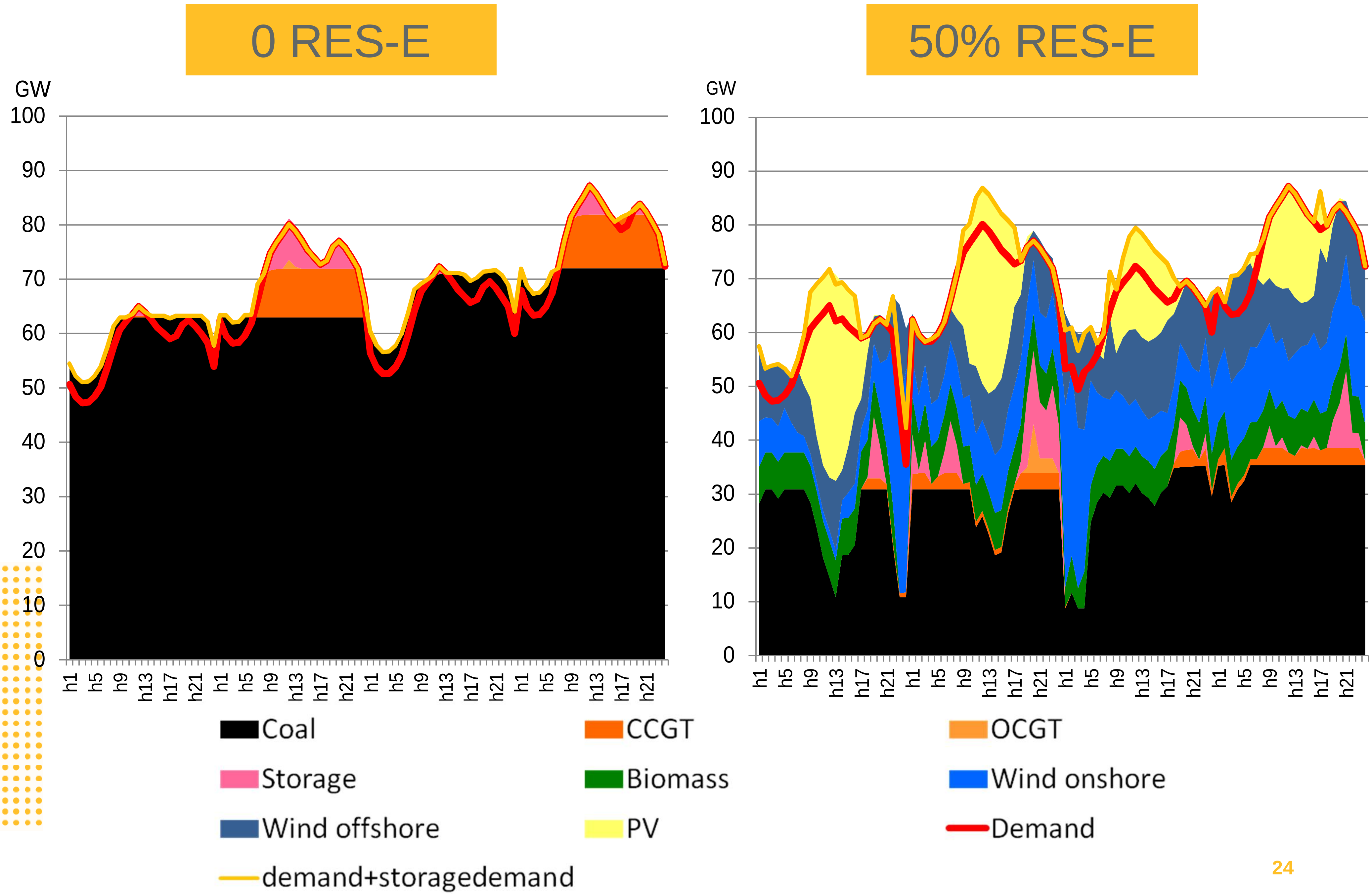
Table 3: Investment costs of conventional and storage technologies in €$_{2010}$/kW

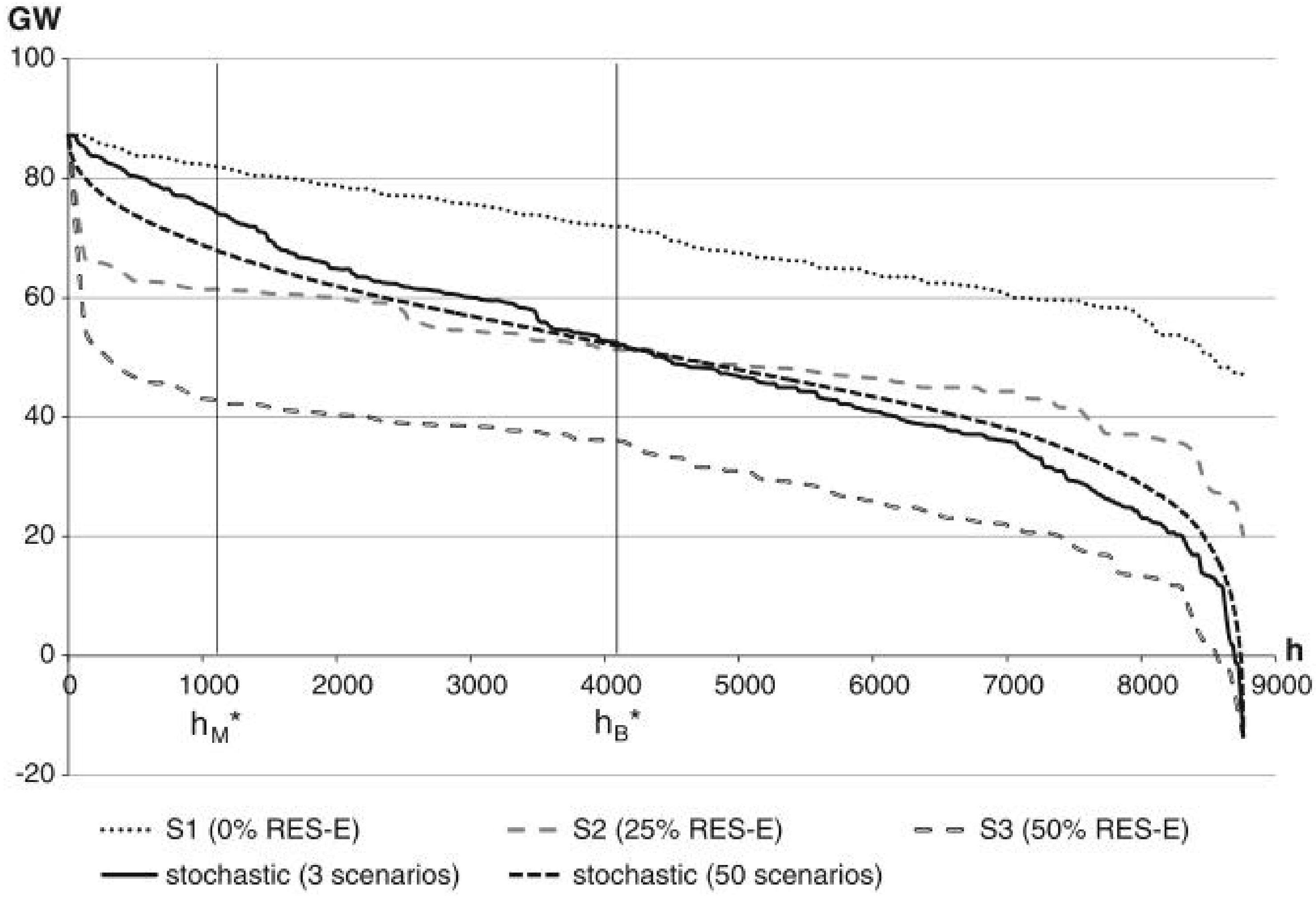
Technologies	2020	2030	2040	2050
Nuclear	3,157	3,157	3,157	3,157
Hard Coal	1,500	1,500	1,500	1,500
Hard Coal - innovative	2,250	1,875	1,750	1,650
Hard Coal - innovative CHP	2,650	2,275	2,150	2,050
Lignite - innovative	1,950	1,950	1,950	1,950
Lignite - innovative CHP	2,350	2,350	2,350	2,350
OCGT	400	400	400	400
CCGT	800	800	800	800
CCGT-CHP	1,100	1,100	1,100	1,100
Pump storage	-	-	-	-
Hydro storage	-	-	-	-
CAES	850	850	850	850

Table 4: Economic-technical parameters for conventional and storage technologies

Technology	$\eta(\eta_{load})$ [%]	η_{min} [%]	availability [%]	FOM-costs [€$_{2010}/kW$]	Lifetime [a]
Nuclear	33.0	28.0	84.5	96.6	50
Hard Coal	46.0	41.0	83.75	36.1	40
Hard Coal - innovative	50.0	45.0	83.75	36.1	40
Hard Coal - innovative CHP	22.5	17.5	83.75	55.1	40
Lignite - innovative	46.5	41.5	86.25	43.1	40
OCGT	40.0	20.0	84.5	17	20
CCGT	60.0	50.0	84.5	28.2	30
CCGT-CHP	36.0	26.0	84.5	40	30
Pump storage	87.0 (83.0)	87.0	95.25	11.5	100
Hydro storage	87.0	87.0	90.75	11.5	100
CAES	86.0 (81.0)	86.0	95.25	9.2	30

Illustrative example – deterministic results




GW
100
80
60
40
20
0
-20
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
h
h_M*
h_B*
S1 (0% RES-E)
S2 (25% RES-E)
S3 (50% RES-E)
stochastic (3 scenarios)
stochastic (50 scenarios)